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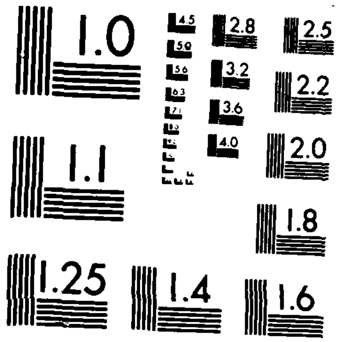

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Staged Inductive Pulse Generator with Capacitive Current Source

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A pulse generator for testing fast opening, vacuum switches that uses vacuum inductive energy storage with an economical capacitor bank current source and copper-wire fuses for the first stage opening switch is now operational. Initial, low level tests with a self-closing output switch result in an output pulse current of 450 kA and risetime of 0.6 μs.

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CONTENTS

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STAGED INDUCTIVE PULSE GENERATOR WITH CAPACITIVE CURRENT SOURCE

I. INTRODUCTION

A pulse generator, Pawn, employing inductive energy storage has been assembled at the Naval Research Laboratory (NRL) using newly developed high energy density capacitors[1] as the primary energy store. These capacitors energize a vacuum coaxial inductor and wire fuses provide the first stage of pulse compression. The capacitor bank[1] for primary energy storage (1 MJ at 44 kV) is one of several identical banks designed and fabricated at Maxwell Laboratories, Inc.(MLI), San Diego. The nominal 20-μs current pulse available from the discharge of this bank serves to energize the storage inductance. Pulse compression is obtained, in stages, by the opening of circuits with increasingly fast switches. The Pawn module provides a test facility for development of the fast, vacuum switches and related technology necessary for the development of high energy inductive storage pulses. In parallel with this effort, a proof of principle system utilizing 6 parallel modules coupled to a common load through separate vacuum coaxial inductors and pulse compression stages (CHECMATE) is being assembled at MLI.[2] The initial goal of both systems is to demonstrate the feasibility of using relatively inexpensive, high energy capacitor technology to generate multi-megampere current pulses of ≈ 100-ns duration. Results obtained from these systems may ultimately be used in the design of a ≈20-MJ, ≈20TW pulser facility to be located at NRL.

Manuscript approved August 13, 1986.

Section II of this paper describes the design, operation, and initial results of Pawn. Its performance is illustrated by the time-dependent currents and fuse voltage obtained during preliminary tests with half of the capacitor bank charged to 23 kV. These preliminary tests used a self-closing output switch and resulted in peak output current of 450 kA with 0.6-μs risetime. Successful operation of this pulse generator greatly depends on the performance of the fuse opening switch and the vacuum flashover output switch. Sections III and IV briefly discuss the development of these two components, respectively (CF Ref. 3 for more complete details). Conclusions are given in Section V.

II. PULSE GENERATOR

A. System Description

The system components are identified in Fig. 1. The pulse generator comprises a 14-ft high capacitor array; a vacuum coaxial inductor attached to the capacitor bank via parallel transmission plates and a high current, low voltage, vacuum feedthrough; a fuse array contained within an enclosure; a vacuum flashover output switch; and a test load. The capacitor bank[1] is divided into four sub-modules, each containing five, 52-μF capacitors rigidly connected in parallel in a low inductance configuration. Each submodule is connected to the common transmission line in series with a protective, stainless-steel, 14-mΩ resistor and a high energy, pressurized, railgap switch. The low voltage vacuum feedthrough resembles a capacitor header and was designed by MLI. The coaxial, energy storage inductor is made of aluminum pipe with welded flanges and connects to a load coupling tee. This tee section provides mounting surfaces for connecting two coaxial fuse enclosures (up and down) and a coaxial load and output switch

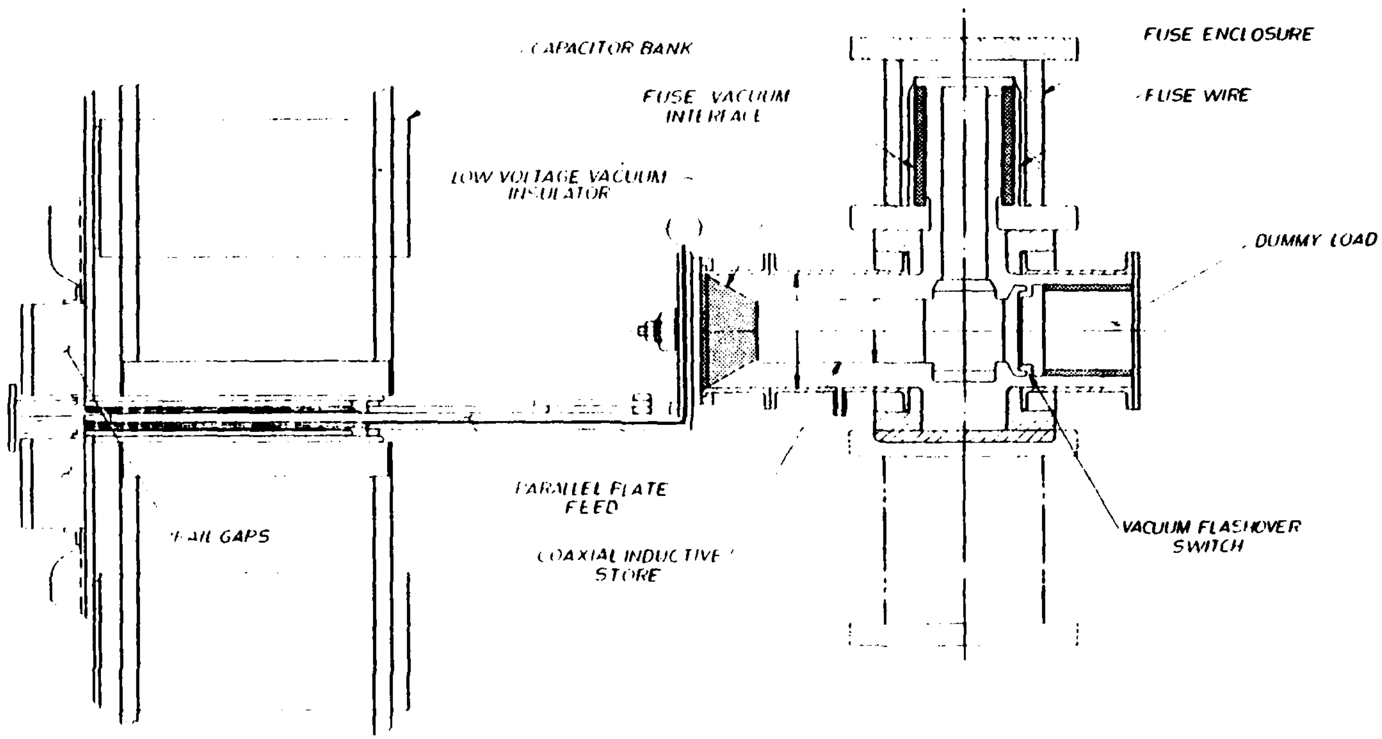


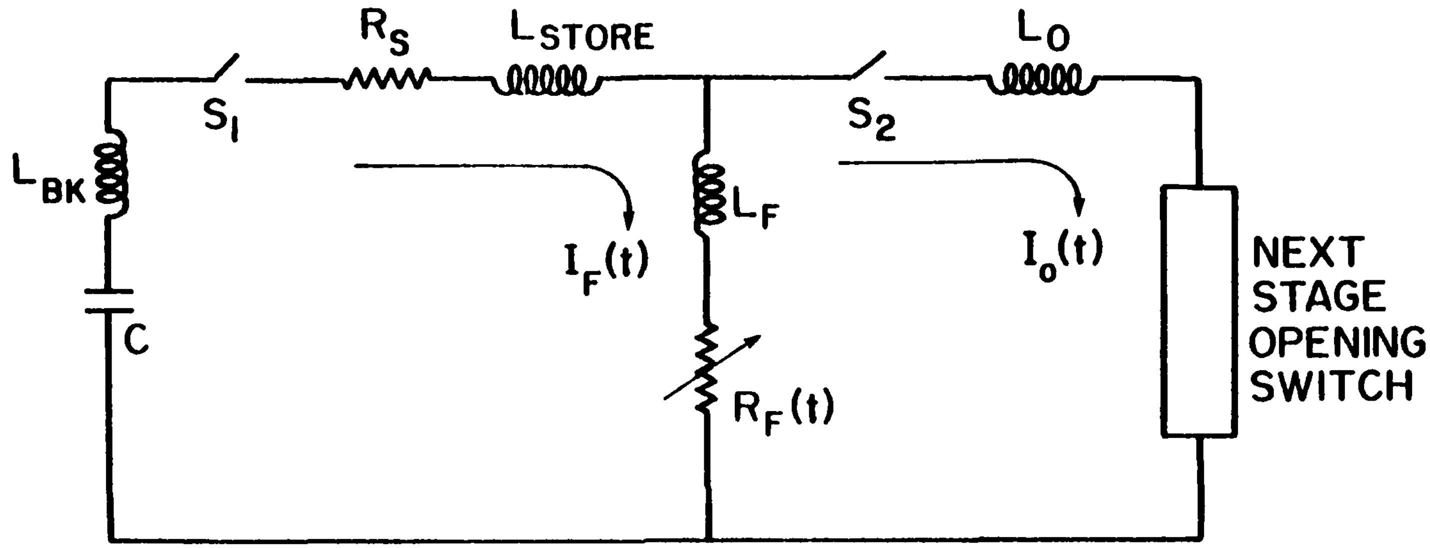
Fig. 1 — Schematic illustration of Pawn System

assembly. The fuse enclosures are made of polyurethane. They must provide for insulation of any high voltages present and contain space for the fuse wires immersed in a tamping medium of either water or pressurized gas. Along with the output switch the load assembly as shown in Fig. 1 contains an electrolyic resistor used as a dummy load during testing of the pulse generator. In future pulse compression experiments this load will be replaced by experimental opening switch stages and an active load.

B. Electrical Circuit and Operation

A schematic diagram of the equivalent electrical circuit for this pulse generator is shown in Fig. 2. The total bank capacitance, represented by C, is 1026 μF. The series resistance, R_s = 4.7 mΩ, comprises the internal resistance of the capacitors and railgap switches (S_1), the parallel safety resistors, and the skin resistance of the conductors associated with the transmission plate and coaxial inductor. The internal inductance of the bank, L_{BK}, including switches and transmission plates, is estimated to be 40 nH. The calculated inductance of the coaxial storage inductor, L_{STORE} is 70 nH. The parallel leg of the circuit represents the fuse assembly with inductance L_F and a variable resistor $R_F(t)$ symbolizing the time-dependent resistance of the fuses. The calculated inductance for the single fuse assembly shown in Fig. 1 is 70 nH. This value would be cut in half by connection of another, identical fuse assembly in the space provided below the tee section.

In operation the capacitor bank is initially charged to a voltage in the 20-kV to 44-kV range. When it is discharged by closure of the railgap switches it produces a quasi-sinusodial



$R_S = R_{BK} + R_{SKIN}$

$L_S = L_{BK} + L_{STORE}$

$S_1 \rightarrow$ RAILGAP SWITCHES

$S_2 \rightarrow$ VACUUM FLASHOVER SWITCH

Fig. 2 — Equivalent circuit for Pawn System

pulse of current, $I_T(t)$, in the storage inductor and fuse array. Prior to each shot, the number of fuse wires to be installed is selected so that the fuses will open just after the inductor is fully energized.[4] The important current density data needed to make this selection were obtained by scale model measurements. These measurements, briefly described in Sec. III, also provide data needed to choose the proper fuse length for a short opening time. Just before the fuses open, the series switch, shown as S_2 in Fig. 2, is closed. The voltage pulse resulting from the increasing fuse resistance will then commutate current from the fuse into the output leg of the circuit. This output leg is shown in the circuit as an inductance L_o in series with an arbitrary element representing some fast opening switch device to be studied or a dummy load.

C. Testing and Performance

The capacitor bank and switches were operated at 40 kV (800-kJ stored energy) with no inductive store or fuse section and delivered 1.7 MA into a resistive load both at MLI and after shipment and reassembly at NRL. The performance of the vacuum inductor and tee section was tested by replacing the fuses with a 5-mΩ, high-current resistor and discharging the capacitor bank at 34 kV to provide a 1.5-MA current pulse. The triggered vacuum closing switch (S_2 in Fig. 2), described in Sec. IV, is still under development. The performance of the pulse generator with a preliminary version of the switch operated in the self-closing mode is illustrated by the current and voltage waveforms of Fig. 3. This data was obtained using only half of the capacitor bank charged to 23 kV, one fuse package, a 35-nH output inductance, and a 30-mΩ resistive load in place of the next stage opening switch of

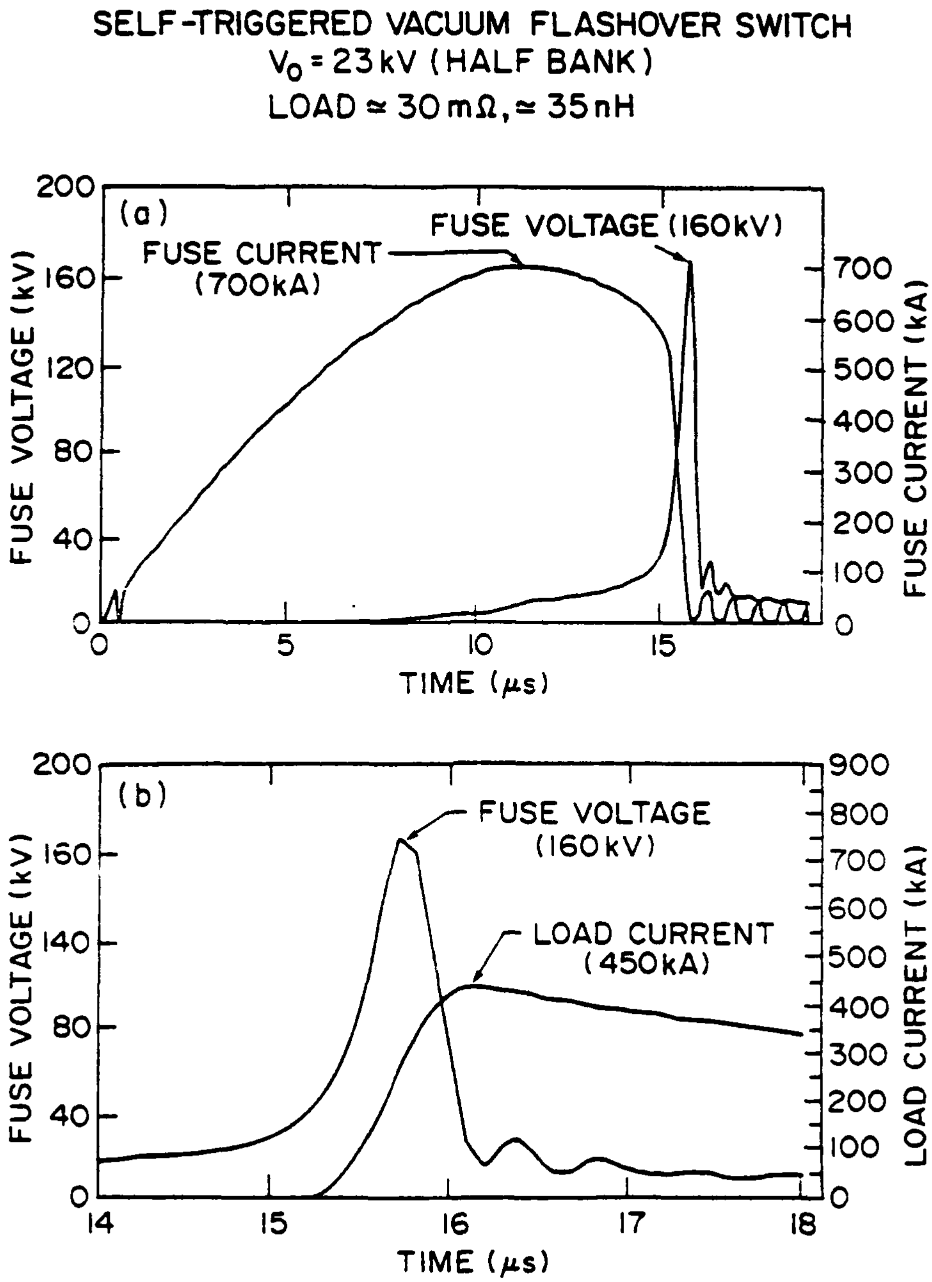


Fig. 3 — Data obtained from a low power, half bank shot using a 30-mΩ dummy load and a self-closing output switch. The fuse current, fuse voltage and load current are shown. Note that the time scale on the lower graph is expanded and begins 14 μs into the discharge.

Fig. 2. The fuse consisted of 50 parallel, #27 copper wires, each 26-cm long. The time-dependent load current shown on an expanded time scale in the lower portion of figure has a 10-90 risetime of 0.6 μs. This represents a pulse compression ratio (energizing time for inductor with no fuse/risetime of current into load) of ≈ 30. The voltage gain, defined as the ratio of initial capacitor charging voltage to peak voltage across the fuse, is 7.

III. FUSE SWITCH

A. Fuse Development Measurements

The first requirement of the fuse is that it conduct during the interval required for the capacitor bank to fully energize the inductor. This interval is approximately equal to the quarter period of the undamped LC circuit involved. This quarter period may be expressed as $T/4 = (\pi/2)CV_o/I$ where C and V_o are the bank capacity and charge voltage and I is the peak current. For a desired peak current of 3 MA, the capacitor bank requires a switch conduction time of 20 μs. With the current specified, the conduction time of a fuse, often referred to as its time-to-explosion, is determined primarily by its cross sectional area.[4] Thus, the fuse cross section must be selected to give a time-to-explosion of approximately 20 μs when driven by a nearly sinusoidal current pulse.

The fuse data needed for design of this stage switch were obtained in a small Fuse Test Facility (FTF). Arrays of parallel copper wires were exploded using a 3-kJ capacitor discharge circuit with a 20-μs quarter period and the current adjusted to produce a 20-μs time-to-explosion. With the same current density, smaller diameter wires were found to open more rapidly. A wire size of #27 AWG (361-μm diameter) was finally selected because it appeared to

provide adequately short opening time without being unmanageably fragile. For details of this work, as well as the other fuse work briefly described here, see Ref. 3.

An idealized concept of a fuse acting as a circuit-opening switch requires that the electrical circuit supply just enough energy to turn it into a highly resistive vapor. If the dissipated energy density is too small, the fuse is not completely vaporized. If the energy density is too large, it may become ionized. In either case the fuse resistance remains small enough that the circuit is not effectively opened.[4] The optimum energy density for these fuses were determined by exploding wires of various lengths in the FTF using a constant-energy test circuit. This effectively varied the final energy density delivered to the fuse while keeping its time-to-explosion constant. From these tests the optimum fuse was selected as being the one generating the highest voltage upon opening. (This corresponds to the shortest opening time.) For this optimum fuse, the scaled energy density (i.e., energy density calculated as if the wire length and cross sectional area maintain their room temperature values) was found to be 4.5×10^{10} J/m^3.

B. Circuit Element Representation

For design and optimization of the inductive pulse generator, the analysis of its electrical circuit must include the non-linear, time-dependent resistance of the fuse.[5] Since the energy dissipated in a resistive circuit element is easily calculated, a simple relationship between energy density and resistivity would be a valuable aid for predicting values of fuse resistance. Unfortunately such a relationship cannot be provided in general because during the explosive vaporization of the fuse its resistance is also influenced by the accompanying time dependent

processes of pressure increase and expansion of the conducting channel. However, for this pulse generator, it is desirable to operate with the optimum fuse having a particular final energy density of 4.5×10^{10} J/m^3. A representation of scaled resistivity as a function of scaled energy density was formulated from the electrical measurements for that particular case.[3] When this model of energy-dependent resistivity is used in numerical circuit analyses with fuse dimensions or circuit parameters adjusted to result in a final energy density of 4.5×10^{10} J/m^3, the calculated currents and voltages should agree with those observed in the operation of a circuit employing the optimum fuse.

This model was used to analyze the data displayed in Fig. 3. The results of this analysis are shown in Fig. 4. The calculated and measured output current waveforms agree as asserted in the previous paragraph. The value of the parameters used in the analysis are listed in Fig. 4. It was assumed that the vacuum flashover switch closed when 20 kV was across it, compared with the measured value of 25 kV.

C. Late-Time Voltage Recovery

When this generator is later used with fast opening, vacuum switches and high impedance loads, the high voltage appearing at the load places an additional requirement on the fuse. Not only must it open quickly, it must withstand a subsequent high voltage pulse without reclosing. This problem is presently being addressed by experiments in the FTF using a small capacitor discharge circuit (set for a 20-μs time-to-explosion) to which is added, in parallel with the fuse, a closing switch and another, faster fuse stage.[3] When the first fuse begins to open the switch closes and the circuit current is commutated into the second fuse. After some

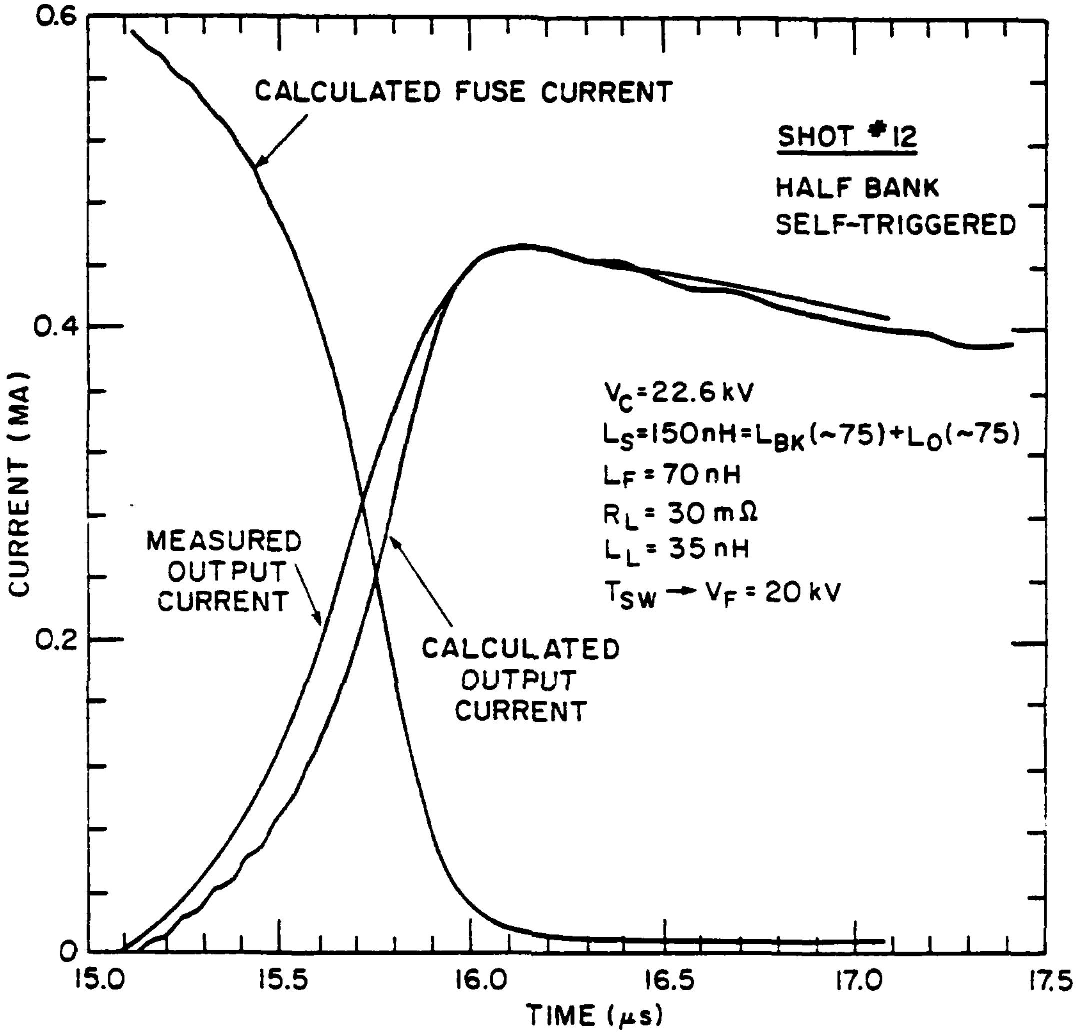


Fig. 4 — Analysis of the shot illustrated in Fig. 3 using the time dependent fuse resistivity model obtained from the FTF

time delay, determined by the diameter of the second fuse, this second fuse explodes generating a voltage pulse across the parallel first fuse. In this way the influence of various surrounding media, delay time, and geometry on the hold off capability of the first fuse are studied. These experiments are not complete (CF Ref. 3). However, initial results with the fuse wires surrounded by high pressure gas indicate that the first fuse can withstand up to 25 kV/cm when the voltage pulse generated by the second fuse is applied 1-2 μs after the first fuse explodes.

IV. VACUUM FLASHOVER SWITCH

A closing switch (shown as S_2 in Fig. 2) is required to isolate the subsequent switching and load stages from the long, low-level voltage pulse present while the inductor is being energized. This switch must operate in vacuum, remain open during the long voltage pulses, and close upon command at a voltage of 20 kV to 50 kV when the fuse begins to close. The jitter in closure time should be less than 100 ns, particularly when used in the multi-module configuration. Further, since the switch must carry currents of 2 MA, the discharge should envelop the entire switch perimeter to avoid localized damage.

A vacuum insulator flashover switch was considered for this requirement based on vacuum flashover tests and ultra-violet (uv) stimulated breakdown tests.[6] An experimental study of switch performance is permitted by a switch-test configuration constructed within an easily demountable vacuum chamber. This configuration is essentially a conical frustum of insulator held between a pair of plane, parallel, circular electrodes. Sinusoidal voltage pulses are applied to the electrodes by a triggered, LC voltage doubling

circuit. The switch insulation may be illuminated radially or axially by small trigger elements that produce both plasma and uv. Each of these trigger sources is a 2-mm long surface discharge driven by a 0.3-μs risetime current pulse from a 0.5-μF, 2-kV capacitor. These sources may be pulsed repeatedly (a few hundred shots) without significant erosion of the surface or electrodes. For details of the work described below see Ref. 3.

A. Self Break Testing

The test fixture was used to evaluate the insulator surface breakdown behavior (self-break) at voltages to 100 kV and with risetimes between 1 μs and 30 μs. It was found that cast polyurethane was superior to both lucite and high density polyethylene for repeated breakdowns. The upper portion of the curve in Fig. 5 shows the range of breakdown voltage obtained for this material with 6.35-mm gap and 45° angle.[6] This scatter suggests that command triggering is essential for predictable operation of a switch.

B. Triggered Operation

Tests were conducted using single and multiple trigger sources of uv and plasma positioned within the vacuum envelope. First, with the source positioned radially with respect to the conical insulator, the separation between the insulator surface and source was varied from 0.5 cm to 12 cm. Although a small delay was introduced with increased distance, the jitter in switch closure remained less than 100 ns, provided the applied voltage exceeded 50% of self-break voltage and the insulator surface was directly illuminated by the source. When the triggering source was removed from line of sight of the insulator, the switch continued to close, but with delays of 5 μs to 20 μs and unacceptable jitter.

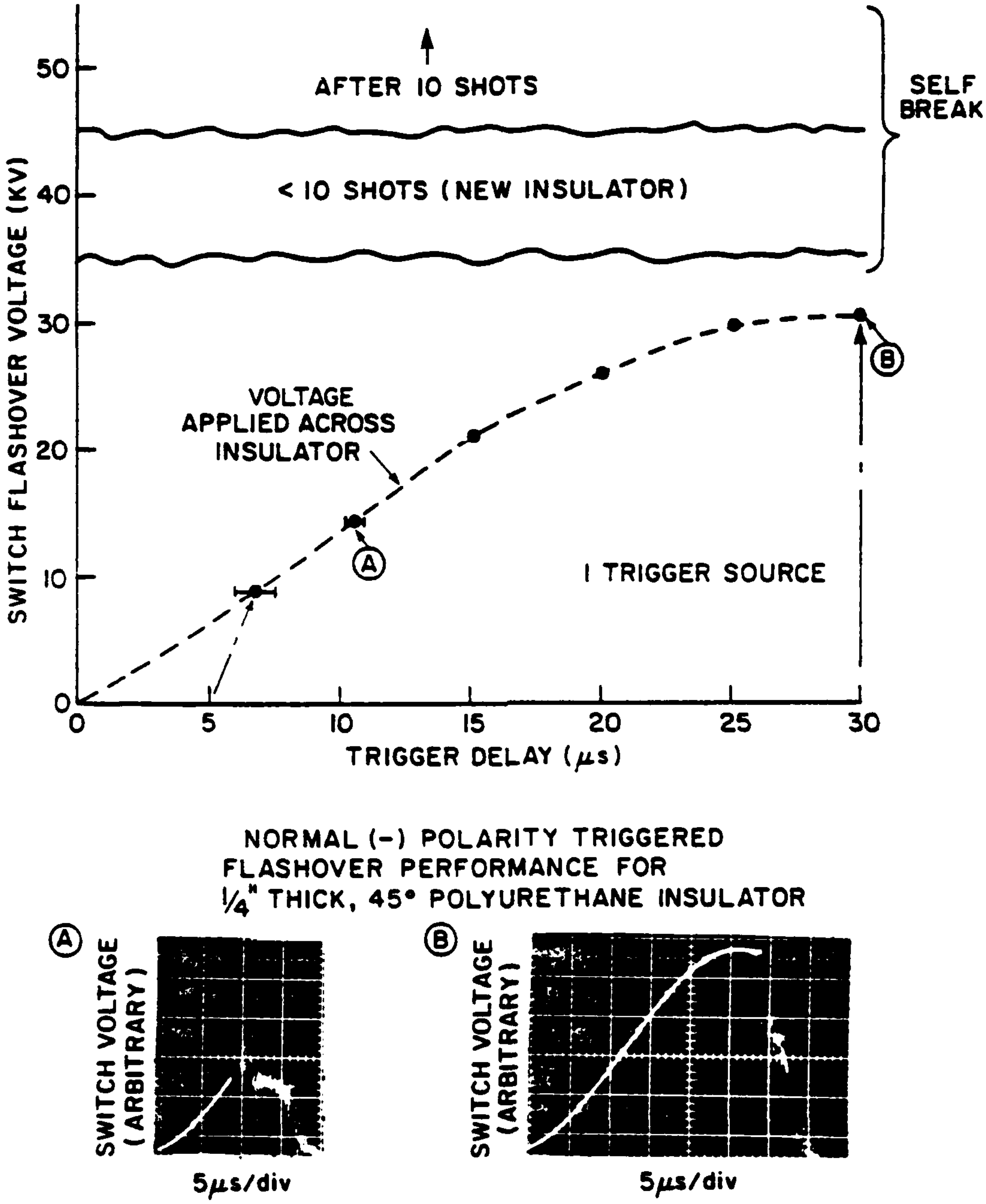


Fig. 5 — Tests results for self-break and triggered operation of a 6.35-mm flashover switch gap using a polyurethane insulator having preferred polarity and 45° cone angle (CF Refs. 3 and 6)

In other tests the trigger source was allowed axial line of sight illumination of the insulator surface through a small hole in the switch electrode. For this configuration, triggering at various times during the rise of voltage across the 6.35-mm switch gap produced results shown by the curve of Fig. 5. Switch jitter is less than 100 ns when applied voltage exceeds 50% of self-break. Reliable triggering occurs at voltages lower than 50% of self-break, but both delay and jitter become severe. For example, the dotted arrow originating at the 5 μs marker indicates that, although the trigger pulse occurred at 5 μs (approximately 6 kV across the switch), closure occurred after a 2-μs delay, with a jitter of 1 μs.

Finally, and most importantly, results of open-shutter photography suggest that for both self-break and triggering, switch closure occurs at discrete points rather than as a diffuse discharge. For self-break and single trigger source closings, only one current channel was seen. In the case of multiple trigger sources, each source appears to initiate its own channel.

Because of delays in packaging the trigger source, the system test illustrated in Fig. 3 was carried out using a vacuum flashover switch operated in the self-closing mode. The difficulties in achieving the required timing for switchout with this configuration suggest that command triggered operation is desirable.

V. CONCLUSION

The PAWN inductive store generator has been successfully tested at low power. The fuse opening switch provides a factor ≈ 30 in pulse compression. The forthcoming higher power tests, using an improved fuse package and a triggered vacuum flashover

switch will determine the viability of this approach for the design of high power generators.

VI. ACKNOWLEDGMENTS

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